UCRL- 92212
PREPRINT

Magnetic Fusion 1985: What Next?

T. Kenneth Fowler

Keynote address at the Sixth Topical
Meeting on the Technology of Fusion
Energy, American Nuclear Society,
San Francisco, CA - March 3-7, 1985

March 1985

DISCLAIMER

Magnetic Fusion 1985: What Next?*+

T. K. Fowler
Lawrence Livermore National Laboratory
University of California
March 04, 1985

ABSTRACT

Recent budget reductions for magnetic fusion have led to a re-examination of program schedules and objectives. Faced with delays and postponement of major facilities as previously planned, some have called for a near-term focus on science, others have stressed technology. This talk will suggest a different focus as the keynote for this conference, namely, the applications of fusion. There is no doubt that plasma science is by now mature and fusion technology is at the forefront. This has and will continue to benefit many fields of endeavor, both in actual new discoveries and techniques and in attracting and training scientists and engineers who move on to make significant contributions in science, defense and industry. Nonetheless, however superb the science or how challenging the technology, these are means, not ends. To maintain its support, the magnetic fusion program must also offer the promise of power reactors that could be competitive in the future. At this conference, several new reactor designs will be described that claim to be smaller and economically competitive with fission reactors while retaining the environmental and safety characteristics that are the hallmark of fusion. The American Nuclear Society is an appropriate forum in which to examine these new designs critically, and to stimulate better ideas and improvements. As a preview, this talk will include brief discussions of new tokamak, tandem mirror and reversed field pinch reactor designs to be presented in later sessions. Finally, as a preview of the session on fusion breeders, the talk will explore once again the economic implications of a new nuclear age, beginning with improved fission reactors fueled by fusion breeders, then ultimately evolving to reactors based solely on fusion.

* "Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48."

+ Keynote address for the American Nuclear Society, Fusion Energy Division, sponsoring the Sixth Topical Meeting on the Technology of Fusion Energy, March 3-7, 1985 at the Sheraton-Palace Hotel in San Francisco, California.

Magnetic Fusion 1985: What Next?

T. K. Fowler
Lawrence Livermore National Laboratory
University of California
March 04, 1985

Keynote address for the American Nuclear Society, Fusion Energy Division, sponsoring the Sixth Topical Meeting on the Technology of Fusion Energy, March 3-7, 1985 at the Sheraton-Palace Hotel in San Francisco, California.

Thank you for inviting me to open this meeting.

I believe that this could be an historic occasion, for today, fusion is at a crossroads. On the one hand, after many years struggle, the scientific feasibility of fusion is almost within our grasp. Indeed, the probability that fusion reactors of several types could be made to work given time and resources is no longer much in question in technical circles around the world. On the other hand, the lack of urgency for new energy sources and the high cost of fusion research have, at this moment of triumph, conspired to put brakes on our efforts.

What can we do, as scientists and engineers engaged in fusion research, that will make a difference? We can, of course, continue in forums such as this to make our work known to other scientists and engineers and to the public at large. Engaged as we are in everyday activities, it is easy to forget how truly remarkable are the accomplishments that we have been privileged to witness and to participate in. When you tour Livermore on Thursday, look around not only as a practitioner, but imagine how you would convey to a layman what it means to have created a Nova laser, or the yin-yang superconducting magnets for the Mirror Fusion Test Facility, or similar accomplishments in your home institutions.

This is indeed high technology, with all the hope and promise that this implies. Perhaps some in the audience are not aware of a new international effort to revitalize the industrial economy of Europe, America and Japan in part through the vehicle of new technology. Now in its fourth year, this effort is carried out through annual meetings of seven heads of state including President Reagan. It is called the Summit Process. Recognizing the potential importance of high technology in Western economies, the Summit Process includes magnetic fusion among a handful of technologies of all kinds singled out for special attention and promise. Recently a Fusion Technology Working Party was created that reports to the Summit Process with responsibility to propose the necessary steps for the development of fusion to be incorporated in individual or joint governmental programs among the nations involved.

Fusion research has also made enormous scientific strides. On contemplating the scientific achievements in this field, such as the recently attained high temperatures in the TFTR that you will hear about later in the morning, it is hard to remember where we started. Yet, when the quest for fusion began back in the 1950's, lasers did not exist and the largest plasma physics devices were little more than the fluorescent bulbs lighting this hall. Even then, everyone knew that what was required was higher density, much higher temperatures and longer energy confinement times. But has it occurred to you that, as seen from today, one or the other of these three critical parameters has increased about a factor of 2 on the average every year for 20, even 30, years?

Yet, however superb the science or how challenging the technology, these are means, not ends. To maintain its support, fusion must also offer the promise of commercial power reactors that could be competitive in the future. This is particularly true of the magnetic fusion program, on which I will concentrate for the remainder of this talk.

In short, we need an ever improving product. What better forum than the American Nuclear Society to critique our efforts? And what more exciting challenge to bring out the inventor in all of us? In his book The Physicists, Cal Tech science historian Daniel Kevles contends that inventors such as Thomas Edison lost out to scientists around World War I when scientists at the University of Wisconsin rather than Edison succeeded in developing sonar detection of submarines. Perhaps, with its blend of forefront science and engineering, fusion is the right home for the modern sophisticated inventor who succeeds because he understands.

Fortunately, a number of our inventive colleagues have already been at work. At this conference, several new magnetic fusion reactor designs will be described that claim to be smaller and economically competitive with fission reactors of the future while retaining the environmental and safety characteristics that are the hallmark of fusion. I know that the presenters of these papers would welcome your critical comments and suggestions. I suggest that, as a service to the magnetic fusion community at large, a critical examination of these designs as to their credibility and promise is the appropriate theme for this conference.

As a preview, let me now discuss briefly three of the new reactor designs that will be presented in later sessions. I will also preview the session on fusion breeders, and conclude with my view of a strategy for the future development of fusion.

Figure 1 shows a small tokamak reactor developed by TRW and Princeton. This design makes use of the possibility that beta values in tokamaks can perhaps be higher than previously anticipated - for example, by entering the so-called second stability regime, or by bean-shaped cross sections. Further experiments will be required to verify that higher beta values can in fact be achieved and to find the best approach for doing so. Reactor studies such as this one help to motivate these experiments. Besides higher beta, this design also incorporates new engineering features that you will hear about later. Some of these features, I might add, have their roots in the mirror research community.

The outstanding feature of this new tokamak reactor design is its small size and power output. What a contrast with 10 years ago when tokamaks were perceived as gigawatt plants at the very least? But is it the right direction? I believe it is, if for no other reason than that a smaller commercial reactor implies smaller developmental reactors as well, and hence a lower development cost for governments to bear until fusion is ready to enter the commercial arena. I remarked earlier that, as we all know, the high cost of fusion research is one of its problems. While expensive engineering development is the norm, the fact that even technical feasibility is expensive for fusion is a special problem that would be alleviated if, by the time we contemplate building experimental reactors, concepts of smaller size and power output could emerge. Tihiro Ohkawa of GA Technologies has a nice way of expressing this. Man imitates nature, he says. To fly, he observed a bird, and feasibility was the flying jenny. For fusion, again man imitates nature, but now the sun. In this case, feasibility experiments may be the largest devices we would ever build, assuming that more knowledge will help us shrink our earthbound suns even more. Clearly concept improvements that whittle down the feasibility barrier would be a big help.

There remains, however, the role of economy of scale at the time that fusion is actually commercialized. Figure 2 shows one approach to this by ganging several small reactors with some components common to all, an approach called multiplexing. Here fusion borrows from fission, for this is also the approach taken by the advocates of small second-generation fission reactors.

Turning to tandem mirrors, Figure 3 shows a small 250 megawatt design now in progress. A 600 megawatt version called MiniMARS is also being carried out in order to test the economy of scale. These are to be compared with the 1200 megawatt MARS reactor that you have seen before. Like MARS, these smaller designs very deliverately incorporate features of inherent safety by passive cooling in the event of an accidental loss of coolant or flow, and also attention to a choice of materials to minimize waste disposal problems by avoiding materials that generate long-lived neutron activation products requiring long-term waste storage. At Livermore, we have long believed that these environmental advantages of fusion are every bit as important as economics if fusion electric power plants are ever to be preferred over other alternatives, by utilities and by the public. At the same time, by virtue of new design features, the smaller MiniMARS actually weighs and costs less relative to its power output than did the MARS or Tokamak STARFIRE designs. As you will hear in later talks, the mass and volume of these small tandem mirrors is in fact the same as comparable second-generation fission reactors such as advanced HTGR's. They even have the same cylindrical shape. Thus these new tandem mirror designs should compete economically with second-generation fission.

The new design features that make possible such size reductions are a new center cell magnet design, in which pancake coils are replaced by more magnetically efficient short solenoids with improved conductors, and new end plugs. The essential feature of the new end plugs is axisymmetric magnetic flux surfaces in the end plugs as well as the solenoidal center cell so that no transition coils are required to join the two. This greatly reduces the length and mass of the end plugs themselves, and, because the thermal barrier length is reduced, it also reduces the center cell length required for ignition. Several ideas have been under study at TRW, and also at MIT and other universities participating in mirror research. Recently at Livermore we have revived another such idea shown in Figure 4. In this design the symmetric flux bundle near the axis is surrounded by octupole coils that apply stabilizing forces at the surface. Unlike the quadrupoles on which yin-yang coils are based, these octupole coils do not disturb the symmetry of flux surfaces near the axis. Actually, the earliest demonstrations of stable mirror confinement employed higher-order multipoles rather than quadrupoles, so there is little doubt that octuploes work in principle. Nonetheless, like high beta in tokamaks, these new end-plug designs would require further experiments that could be carried out in the smaller mirror facilities such as TARA at MIT over the next 3 or 4 years. In the mirror case, since only the end plugs are involved, the best concept could then be implemented in the mainline MFTF program in a relatively short time so that a MiniMARS scientific data base could be established by the early 1990's.

Let me now turn to the reversed field pinch (RFP). Encouraging experimental results in recent years have stimulated new reactor designs based on this concept with a focus on small, low-cost reactor cores using copper magnet coils. Figure 5 shows a Compact RFP reactor that will be discussed in a later session. With wall loadings from 5 to 20 MW/m^2, this reactor minimizes the size and cost per thermal kilowatt of the fusion core. The design shown is for a 1000 megawatt-electric plant; yet, as is shown in Figure 6, the core is only a little larger than the present-day TFTR. Among all fusion candidates, the proponents believe that the Compact RFP comes nearest to meeting the cost competition of present-generation LWR's. More research is needed to determine the actual physics scaling from the present small experiments to reactors. Nonetheless, the Compact RFP is a challenging idea that deserves your scrutiny and criticism during this meeting, as do other reactor concepts that I have not had time to cover here, such as spheromaks, stellarators, and, of course, the inertial confinement reactors.

Let me now say a few words about fusion breeders, or hybrids. Figure 7 shows the motivation. This is taken from a recent review article by Claire Max in the Livermore Energy and Technology Review. I draw your attention to the curves on the right showing cumulative uranium consumption in the U.S. under various assumptions. The shaded area exceeds estimated U.S. resources. The upper curve represents the demand from LWR's in the absence of breeders. As you can see, according to this analysis, without some kind of breeders the U.S. would run out of uranium fuel sometime between the years 2025 and 2050.

On the other hand, the lower curves show that by introducing either LMFBR's or fusion breeders in the interval 2000 to 2020, uranium consumption would level off before 2050. I think you are all familiar with the arguments for chosing the fusion breeder even though LMFBR's are ahead today. The main point is the support ratio, that is, the number of LWR's for which a single fusion breeder can supply fuel. As you know, while LMFBR's essentially must replace LWR's one-for-one, a single fusion breeder can support 5 or 10 or even more fission reactors, depending on the type. Thus, with the fusion breeder, the fuel supply problem can be solved with much lower capital investment in new technologies. And from the fusion point of view, assuming that fission does make a comeback, breeding is surely the earliest application of fusion with a clear economic incentive. According to Claire Max's review article: "One can argue that if the hybrid fusion reactor were to prove economical in about 2005 ... the country could ill afford to miss out on the tremendous potential savings to the domestic energy economy that it represents ($20 to $50 billion between 2010 and 2020, for a range of reasonable assumptions). Nor would we want to miss the opportunity to establish a strong position in the large potential export market for these reactors or the fuel they manufacture."

This brings me to my last topic, a strategy for fusion development. Figure 8 shows a possible development path and ties together all the points I have tried to make. On the left is the barrier representing the high cost of development. As I have said earlier, this is best attacked technically by continuing to stress concepts that can be tested at lower cost as we enter the stage of experimental reactors and engineering development after 1990. This should be a major program focus over the next 5 years and after TFTR and other current efforts it may indeed be the most important contribution that the U.S. program can make to world progress during that period of time. On the right is a schematic of the three main motivations for fusion presented in the order in which I think they would first impact the economy. At the beginning of this talk, I strerssed the high-technology nature of fusion. This is already a strong motivation for industrial participation in fusion research, to generate spinoffs, but as a market motivation I would view it as the most distant in time since, like basic research, it is essentially an appeal to the unknown. The appropriate ordering for the other two fusion motivations that I have mentioned - namely, environmental advantages and an abundant fuel supply - depends on which of two futures comes to pass. One possibility is that depending on such factors as acid rain, coal will follow oil in the next century and fusion will follow coal, mainly from environmental considerations. Another possibility, and the one I had in mind in preparing this slide, is that, aided by fusion, fission will enter a new age of public acceptance by the year 2000. Besides the economic aspects I have already discussed, fusion breeders could set the stage for second-generation fission reactors by providing an adequate fuel supply including the U-233 option. Then, because of the environmental advantages of pure fusion reactors in eliminating long-term waste storage, fusion would gradually replace fission altogether. This is an old vision, but one that deserves re-examination in light of today's knowledge.

Finally, a word about the present. While I have stressed the necessity for competitive reactor products to guide and motivate the program, it is also true that we must continue to make steady progress in our research every year and every day. Whatever the path, fusion development has been and will continue to be a long and arduous process. Only steady progress can sustain us. We cannot expect a fusion revolution but rather a steady evolution, both in experimental progress and improvement in our concepts, and in ultimate acceptance in the commercial world. In a recent examination of the prospects for second-generation fission, a group of distinguished utility executives reached the same conclusion: evolution not revolution. Our task is to convince our supporters in government that, for evolution to continue, fusion research must receive stable support. No one can predict the exact time of need, whether 2000 or 2025 or some other date; nor can they fully anticipate what opportunities the advantages of fusion might present that would accelerate its acceptance in society at that time. I would like to conclude by quoting historical evidence on this point taken from the brilliant treatise on pre-industrial society by the French historian, Fernand Braudel. He writes: "There are times when technology represents the possible, which for various reasons - economic, social or psychological - men are not yet capable of achieving or fully utilizing; and other times when it is the ceiling which materially and technically blocks their efforts. In the latter case, when one day the ceiling can resist the pressure no longer, the technical breakthrough becomes the point of departure for a rapid acceleration."

Thank you.

Figure 1
350 MWe Tokamak

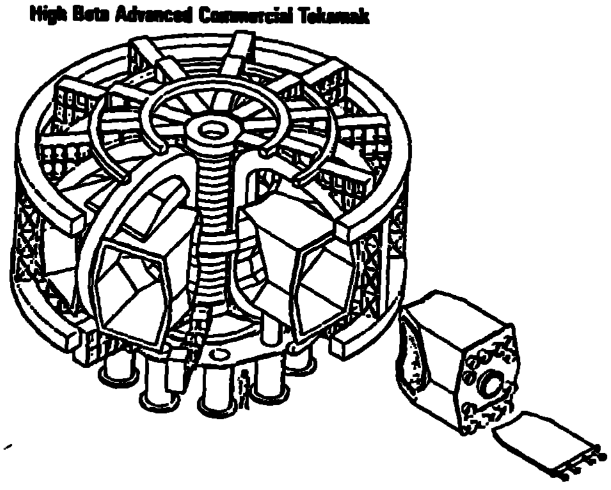


Figure 2
1400 MWe Multiplexed
Tokamak Power Plant

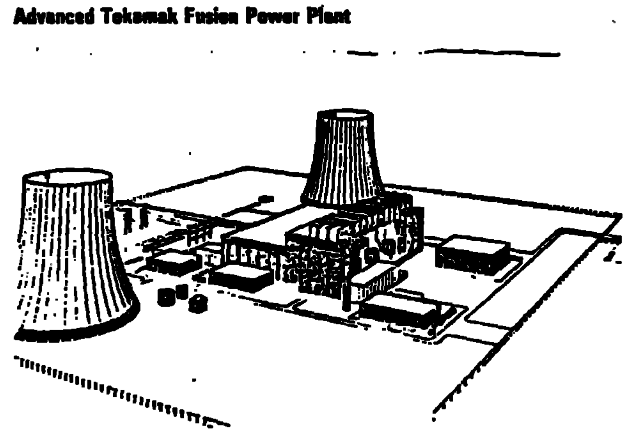


Figure 3

A COMPACT 250MWE TANDEM MIRROR REACTOR

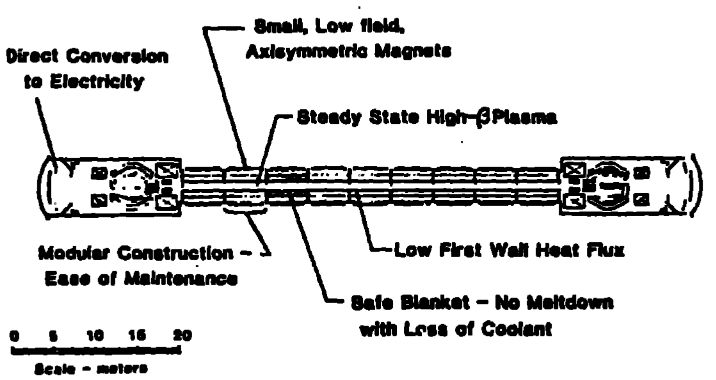


Figure 4

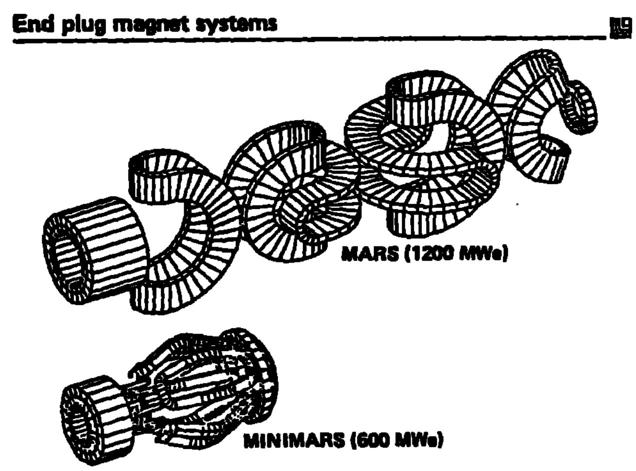


Figure 5

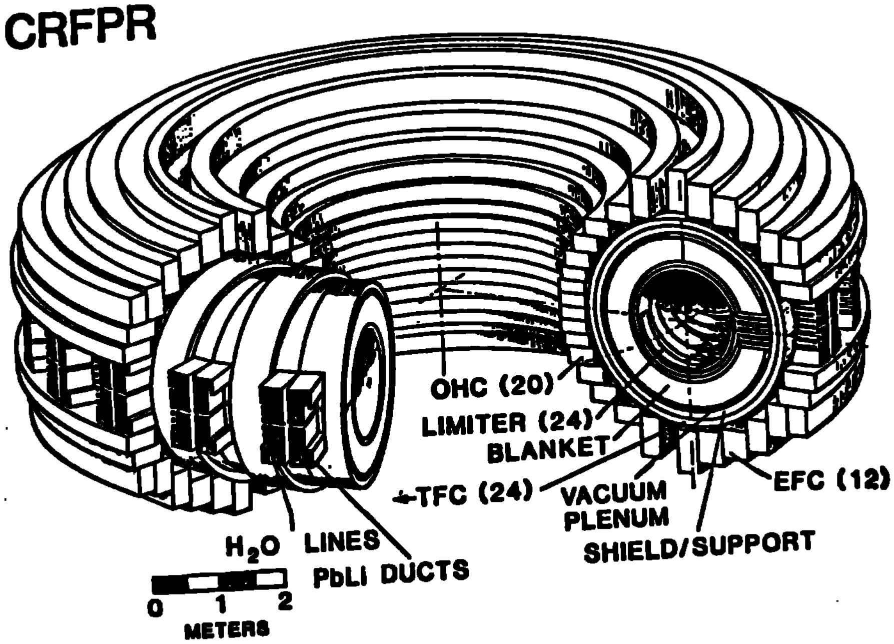


Figure 6

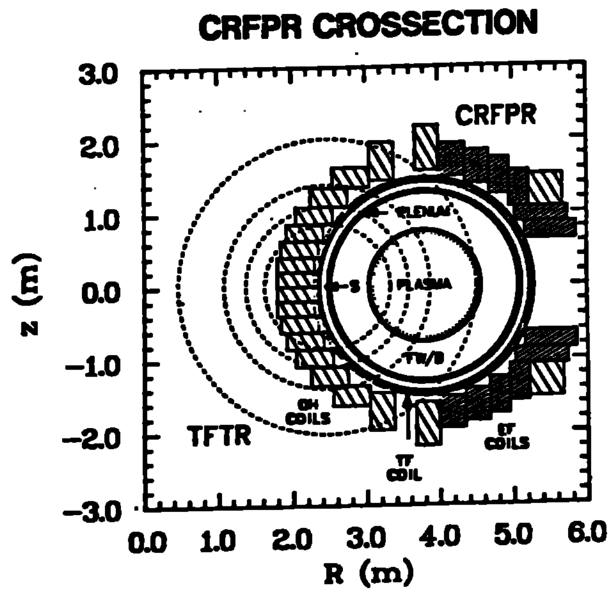
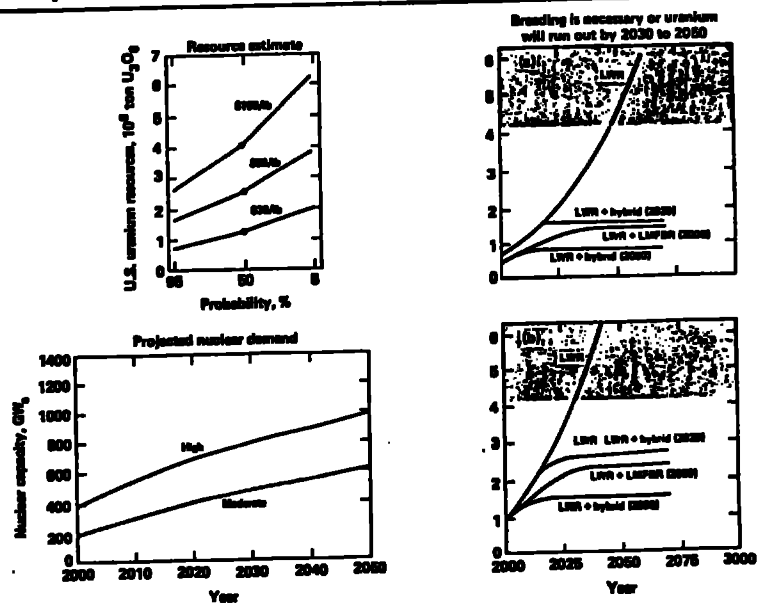


Figure 7

Breeding will be necessary if we are to significantly use fission power



THE ROAD TO FUSION

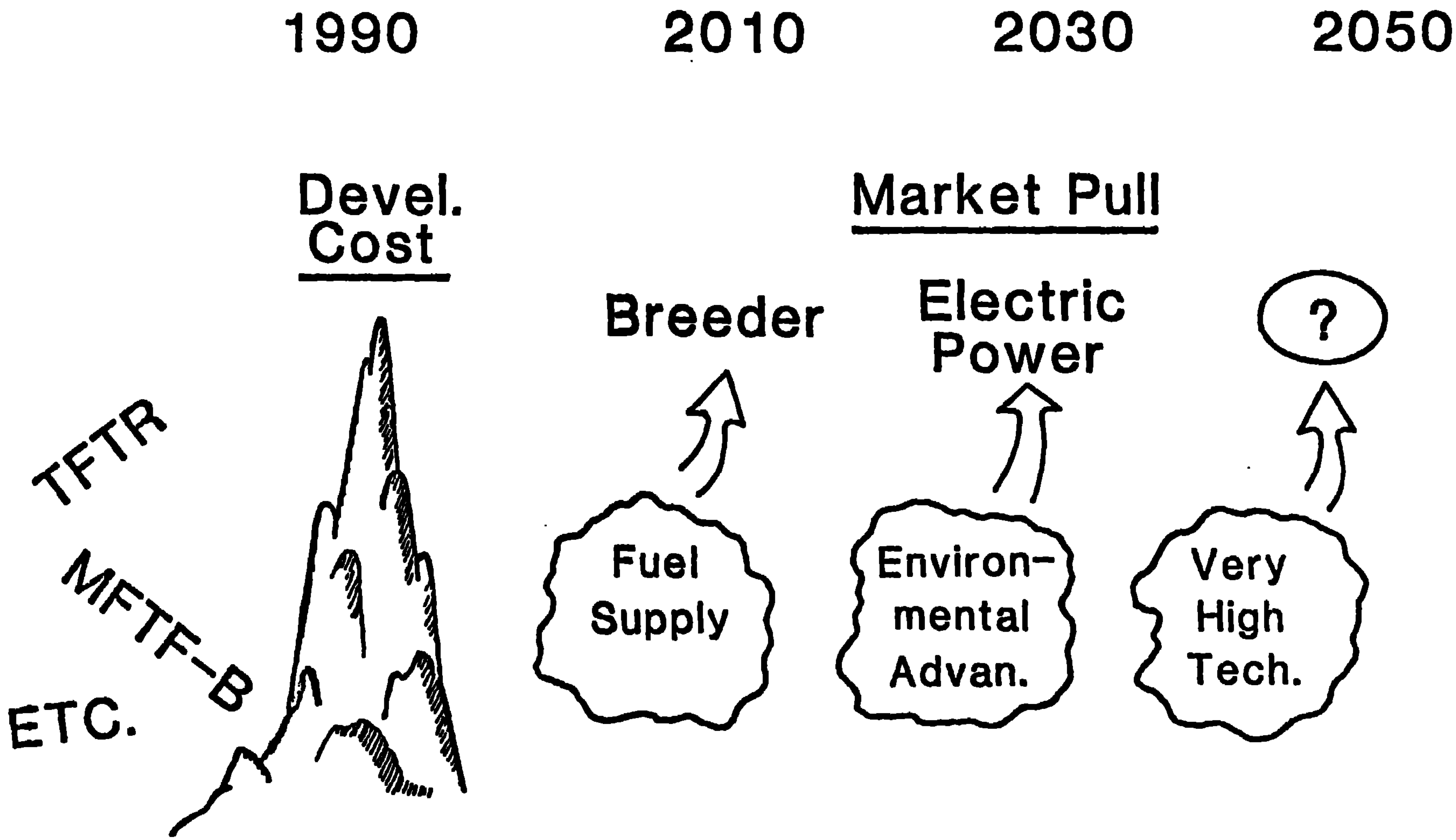


Figure 8